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Impact of increasing steam turbine flexibility on the annual performance of a direct steam generation tower power plant

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Abstract

Among concentrating solar power technologies, solar tower power plants currently represent one of the most promising ones. Compared to parabolic trough configurations, tower systems enable considerable efficiency gains as higher concentration ratios can be achieved. Direct steam generation systems, in particular, eliminate the usage of heat transfer fluids allowing for the power block to be run at greater operating temperatures and therefore further increasing the thermal efficiency of the power cycle. On the other hand, the current state of the art of these systems does not comprise thermal energy storage. Although it has been shown that the integration of storage potentially enhances the economic viability and profitability of the plants, there are no currently available and techno-economically feasible storage integration options for the case of direct steam generation towers.
The lack of storage adds to the already existing variability of operating conditions that all concentrating power plants endure due to the fluctuating nature of the solar supply. This situation is more prominent for the case of direct steam generation systems; leading up to multiple start-ups during a 24h period if the weather conditions are not optimal. In the interest of improving the annual performance and competitiveness of direct steam generation concentrating solar power plants, it is desirable for the plant to achieve fast start-up times to harness the solar energy as soon as possible. The start-up speed of the whole plant is limited by the thermal inertia of certain key components, one of which is the steam turbine.
This paper studies the potential for power plant performance improvement through the increase of steam turbine flexibility at the time of start-up. The methodology consisted of performing sensitivity studies on the annual operation of a power plant while considering different scenarios of turbine operational modifications. For each study, the corresponding power plant performance indicators were evaluated and compared to the base case without modifications. It is shown that gains of up to 7% in total power plant electric output and reductions in turbine maintenance periods can be achieved as a result of the implemented operational improvements.

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1. Introduction

Solar tower systems currently account for 4% of the global installed share of concentrating solar power (CSP) and recent market trends indicate that this technology is set to play an increasingly prominent role within the CSP landscape [1]. However, it is also a fact that the development of new CSP plants is threatened by the relative high costs of the technology, which are not yet competitive with other means of power generation, including other renewables such as solar photovoltaics and wind [2]. Since the readiness level of CSP technologies will continue to mature in the same measure as new power plants are deployed worldwide, it is crucial to reduce the previously mentioned threat for the future generations of CSP. Therefore, it becomes relevant to investigate the existing technology improvement opportunities of currently deployed systems.

In solar tower power plants, the highest impact on the annual electricity generation is given by the varying levels of solar irradiance [3]. This is related to the variation in power plant operating conditions induced by the inherent fluctuations of the solar resource and weather. The impact of such fluctuations is aggravated for systems that do not incorporate thermal energy storage as is the case of direct steam generation solar tower power plants (DSG-STPP). One of the future improvement opportunities for solar tower systems is the consideration of rapid temperature changes in the design and operation the power block [4]. It is desirable for the plant to achieve fast start-up times to harness the solar energy as soon as possible.

From previous experience at the Solar One power plant, the inability to quickly restart the turbine on days with intermittent radiation led to significant energy losses for the power plant [4]. It is therefore the objective of this work to concentrate on steam turbine start-up time improvements. Although steam turbines for solar applications are designed with features which allow a high thermal flexibility, such as the barrel casing design of the high pressure turbine (HPT) and the slim design of the low pressure turbine (LPT) [5][6], operational power plant requirements demand full utilization of this flexibility.

In order to increase the thermal flexibility of steam turbine equipment, start-up constraints must be taken into account. Turbine start times are governed by curves which limit the speed at which the turbine can reach full load. The main purpose of these curves is to maintain temperature gradients in the turbine metal under allowable limits. There are different start-up curves depending on the thermal state of the turbine. In general, the warmer the turbine is before the start, the faster the start-up can be. Therefore, a potential area for increased turbine flexibility involves maintaining higher internal temperatures during idle periods.

In previous works, temperature maintaining modifications have been studied on steam turbines operating in parabolic trough plants [7][8][9]. Results indicated a great potential for maintaining the turbine temperature when combining the application operational modifications, yielding increases in power output of up to 9.5% on the day following a long-cool down and 3.1% improvements in annual power plant performance. Other works have also studied means of changing operating procedures to achieve faster start-up times [12] or to improve the start-up conditions of the turbine [13]. In the present work, the implemented measures involved using heat blankets and high speed barring on the turbine during cool-down. The combined impact of these improvements was measured in the annual operation of a modelled DSG-STPP.

Nomenclature

ACC	Air cooled condenser
CSP	Concentrating Solar Power
CSPP	Concentrating Solar Power Plant
DSG-STPP	Direct Steam Generation Solar Tower Power Plant
EOH	Equivalent Operating Hours
EOHs	Equivalent operating hours due to start
EV	Evaporator
HPT	High Pressure Turbine

LCOE	Levelized cost of Electricity
LPT	Low Pressure Turbine
NOH	Normal operating hours
RH	Reheater
SH	Superheater
TES	Thermal Energy Storage

2. Direct steam generation solar tower plant model

The analysis of the DSG-STPP was performed using DYESOPT, a thermoeconomic modeling tool developed by the authors, which requires location-specific inputs (such as economic indicators, hourly meteorological conditions and electricity pool prices) as well as power plant design specifications and cost functions at the component level. These inputs allow the design of the power plant at nominal conditions to be achieved. Furthermore, the inputs are used for annual performance simulation using TRNSYS, the results from which are finally used for thermoeconomic performance evaluation. Fig 1 schematizes a simplified version of the flow of information and calculations in the tool, where the required input data is differentiated by colors depending on the nature of the data: design configuration related (dark grey), location-related (grey) and cost functions (white). The following sub-sections briefly provide an insight to each of the blocks shown and the steps taken for the modeling of the power plant.

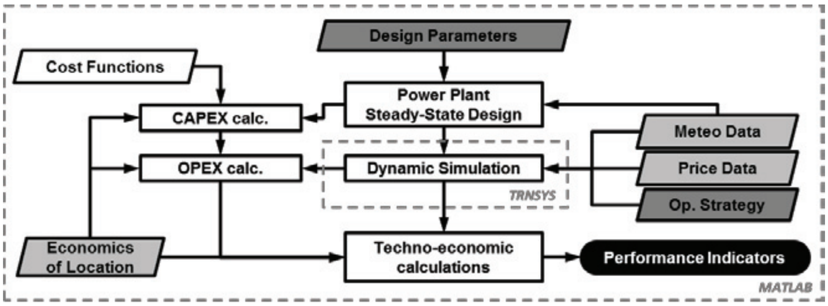

Fig 1 Simplified schematics of information flow in DYESOPT

2.1. DYESOPT inputs

- **Design Parameters:** The typical layout of a DSG-STPP is simple compared to that of CSPPs with thermal energy storage. A DSG-STPP is composed of 2 subsystems: the power block and the solar field-receiver ensemble. For the power block the selected steam cycle corresponds to a reheat Rankine with extractions for feedwater preheating. The selected nominal capacity of the plant was 120MWe with nominal steam inlet conditions of 160 bar and 545 C [15]. Furthermore, the plant was modeled with a deaerator and an air cooled condenser. The solar field was chosen as a surround type heliostat field. The receiver is of external type and is subdivided in three sections: evaporator, superheater and reheater with similar working conditions to those described in [16]. A schematic representation of a DSG-STPP layout is shown in Fig 2.
- **Plant location:** The power plant was modelled for a chosen location near Seville, Spain. For this location a whole year's worth of meteorological data was gathered. The meteorological data used corresponds to typical weather data for the location at coordinates 37°34'N, 2°39'E with a time span of ten minutes as extracted from the HelioClim-3 dataset [14].
- **Operating strategy:** Given the simplicity of the DSG layout and in the interest of showing the cyclic operating conditions imposed by the availability of radiation, a pure solar operation was chosen for the power plant model. The power plant is selected to operate at any point in time in which the solar resource is sufficient to reach acceptable superheated and reheated steam conditions.

- **Cost Functions:** These inputs allow to measure the economic performance of the DSG-STPP. Two performance indicators were considered: the net electrical output and the equivalent operating hours (EOH). The first indicator consists of the MWh produced during a 1 year period. This indicator is inversely proportional to the LCOE. The second indicator is used by manufacturers to establish maintenance requirements of the turbine, which for instance can be linked to the plant availability and thus impact its economic performance [13].The EOH are defined as the sum of the normal operating hours of the plant (NOH) and the equivalent operating hours due to start (EOHs). The NOH are the amount of operating hours. The EOHs can be seen as a penalty factor added to account for the lifetime consumption of the turbine due to the amount of cold, warm and hot start. Each type of start has a different weighting factor in the EOHs, with cold starts weighting more than hot starts.

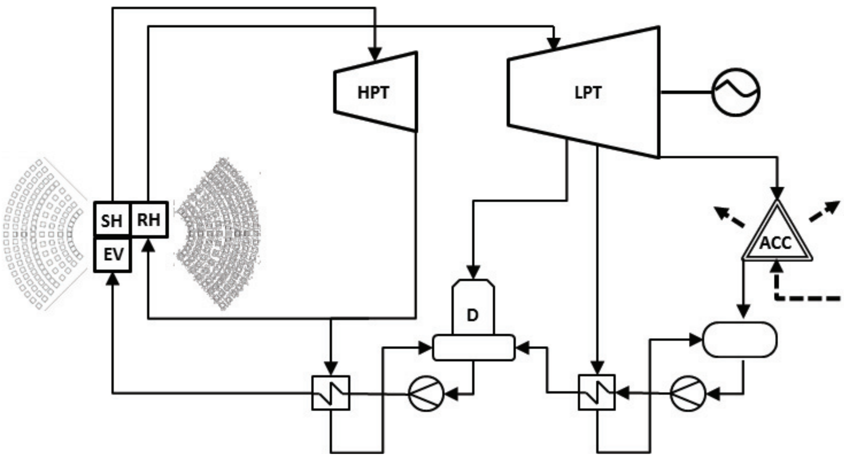

Fig 2 Simplified schematics of information flow in DYESOPT

2.2. Steady-state design and dynamic modeling of the DSG-STPP in DYESOPT

The first process in DYESOPT corresponds to the design of the power plant at nominal conditions (steady state), based on the selected input data described in §2.1. For such purpose, individual steady state models for each of the components in the power plant were implemented. The equations governing these models were extracted from [17](as gathered from[18][19][20]) for the solar field, from [21][22] for the power block and [23] for the DSG receiver. The nominal design allows to size each of the components in the power plant and obtain the relevant information which is needed for the dynamic modeling. In this regard, each of the subsystems in the STPP: the solar field-receiver and the power block have been modelled in detail in the TRNSYS simulation studio [24].

Within TRNSYS, the major power plant components of solar field and power block were modelled using component types from the STEC library [25]. TRNSYS Type 394, for the heliostat field, uses an externally supplied efficiency matrix which maps the solar position to a value of overall heliostat field efficiency. This matrix is determined using an in-house model, described in a previous work [17]. Off-design performance of the power block takes into account variations in efficiency and mass flows as a function of the turbine inlet conditions using the Stodola's ellipse law [26]. The STEC library however does not provide a component type for the direct steam generation receiver. Consequently, components Type 264 and 265 were designed for the evaporator and superheater/reheater based on the equations presented in [23].

3. Turbine temperature maintaining modifications

The speed at which the turbine can start is limited by thermal stress-related constraints and the associated low cycle fatigue [10]. These are directly connected to material properties and to the temperature gradients to which the material is subjected. During start-up, the parameter that drives the temperature transients experienced by the turbine is the temperature difference between the incoming steam and the turbine metal. It is ideal that these two temperatures are as close as possible at the time of start-up in order to avoid elevated temperature stresses in the material. For this reason, the warmer the turbine material is before the start, the faster the start-up can be [12] since the time dedicated to the warming up phase of the turbine can be considerably reduced.

In common power plant operation, the time it takes for the turbine to be operational is determined by start-up curves, which set the rate for the turbine to reach nominal speed and full load. Start-up curves are established by the manufacturer with the purpose to maintain thermal stresses under a given temperature dependent limit [11]. Depending on the initial temperature of critical turbine components or on the time the turbine was off-line, start-ups can be classified as cold, warm or hot. Typical values for start-up type determination are shown on Table 1 [12].

Table 1: Typical values associated for turbine start-up

Start type	Turbine outage [hrs]	Duration [% of cold]
Hot	Less than 6	6-10
Warm	6-48	45-50
Cold	Over 48	100

Given the dependency of the turbine temperature states on the selection of start-up curves, a potential area for increased turbine start-up flexibility involves maintaining higher internal temperatures during offline periods, therefore allowing for faster start-up curves to be implemented. Fig 3 shows the three main types of starts and the potential gains in power production between them. A number of temperature maintaining measures have been studied previously [8][9] through their implementation on a dynamic turbine thermal model[7][27] which allows to predict the transient temperature distribution within the turbine. Out of these studies, two enhancing measures were chosen to be studied on the modeled DSG-STPP. The selected measures comprise the use of electrically powered heat blankets and high speed barring, both of which are explained below.

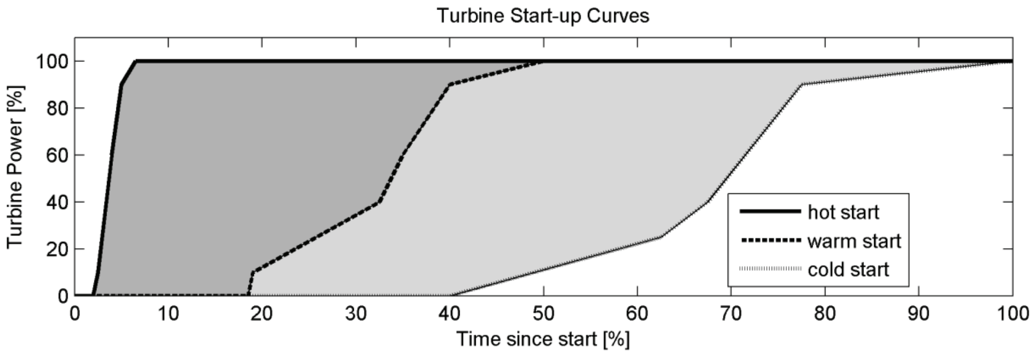

Fig 3 Potential gains in power production between different start-up curve types.

3.1. Electrically powered heat blankets

Heat blankets are implemented on the steam turbine between the outer casing and its insulation layer to the ambient. Therefore, this temperature maintaining modification not only provides heat through the outside walls of the turbine but it also shields it from natural convection heat losses which normally occur through the insulation layer. Different levels of heating can be easily applied to the turbine through the use of this enhancement; however, the results from [7] showed that this measure is only effective for heating the casing of the turbine, leaving the rotor at a colder temperature state. Therefore it is ideal to combine this measure with one that would provide equivalent heat on the turbine inner components. There are no limitations in the range of applicability of heat blankets on a turbine other than their level of electricity consumption.

3.2. High speed barring

During turbine offline operation, the turbine rotor is kept rotating at low rotational speeds in order to avoid bending due to the un-even transient temperature distribution over its surface. At this point of operation a small fraction of stagnant steam remains within the turbine cavity. As a result of the interaction between the recirculating steam and the moving turbine surfaces, friction and ventilation work is produced, see Fig 4. These two phenomena are generally viewed as a problem rather than a solution. Particularly, uncontrolled temperature increases in idling back pressure turbines is a well-known disturbance that results from ventilation [28].

However, from the perspective of maintaining the turbine temperature during cool-down, the effects of friction and ventilation can be viewed as a source of heat within the turbine. The ruling equations of friction and ventilation are proportional to the cube of the rotational speed. Therefore, by increasing the barring speed, the heat source from friction and ventilation will be higher. The effect of high speed barring was studied in [9] yielding relevant temperature increases in both the casing and the rotor of the steam turbine. The range of application this modification is limited by the temperatures reached in the last stage blade of the LPT. For the current study an upper limit was set on this modification based on the studies performed in previous work by the authors.

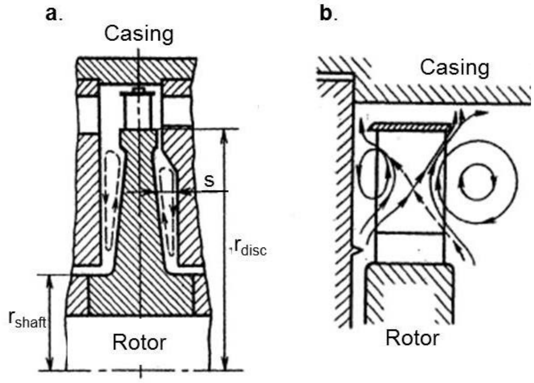

Fig 4 Steam flow paths in the discs and blades of the turbine for (a) friction and (b) ventilation [29].

4. Results

The simulation scheme followed for the studies performed on this paper involved a two-step approach. The first simulation step consisted of running a year of power plant operation in DYESOPT and obtaining the dynamic behavior of the DSG-STPP for the selected operating strategy. The second simulation step consisted in the gradual combined implementation of the heat blankets and the high speed barring. The thermo economic performance of the power plant was calculated in each case and compared with the case with no modifications. The subsequent sections further explain the simulation process along with presenting the obtained results.

4.1. Base case and annual turbine cool down

This first annual simulation of the power plant served as the base case for calculation and comparison for the subsequent simulations with the turbine temperature maintaining modifications. For a given time step in the dynamic simulation, TRNSYS provides the steady state solution of the power plant model. Over a series of time steps, this implies that the obtained results are a quasi-steady state solution of the power plant transient behavior. Depending on the type of study carried out with the simulation tool, this solution is sufficient to capture the more important variations in the power plant. However, the focus of this work is on turbine transient operation, the behavior of which is not fully displayed in the quasi steady state solution.

The transient operation of the turbine was included in the base case results by first performing a characterization of the start-up types endured by the turbine during the simulated year of operation. Fig. 5 displays the annual distribution of turbine cool-down durations and their respective frequencies throughout the year. From this figure and following the time ranges stated in Table 1, it is possible to determine the corresponding start-up types. For the base case it can be seen that the largest amount of turbine starts concentrates in warm types, which is to be expected given that it is the start-up type that comprises the duration of over-night cool downs.

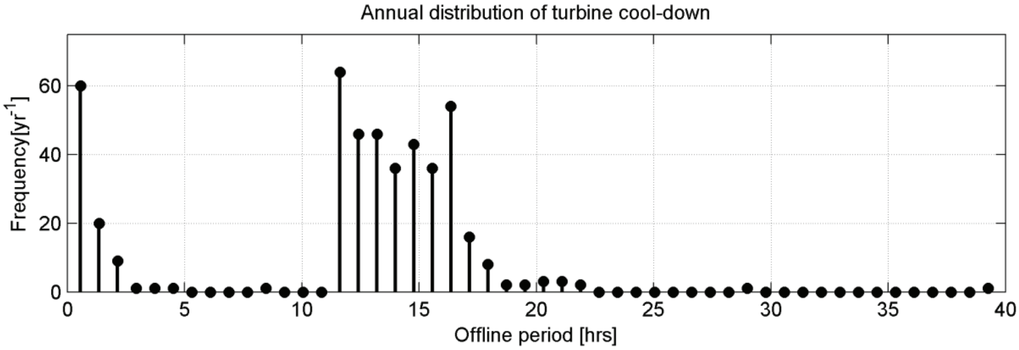

Fig. 5 Turbine cool-down duration and frequency during yearly power plant operation

The classification of the start-up types of the base case had a twofold purpose within the simulation process. On one hand, the knowledge of the type of start-ups in combination with a set of typical start-up schedules obtained from a turbine manufacturer allows the corresponding transient power generation to be reflected (see Fig 3). On the other hand, this original distribution of start-up curves will serve as an input for the subsequent studies performed with the temperature maintaining modifications.

4.2. Impact of temperature maintaining modifications

The simulation stream carried out during the base case and start-up characterization was repeated on this second step with the inclusion of different scenarios of turbine flexibility. With the knowledge obtained from the studies performed in [7][9], a relevant range of application was chosen for the electrically powered heat blankets and the barring speed increase enhancements. A study on the impact of the modification on the plant was then carried out by progressively varying the range of application of the enhancements. In order to evaluate the reduction in turbine start-up time, the temperatures related to the original start-up type distribution from §4.1 were used as the reference final temperatures in the turbine metal after the cool-down periods. The temperature improvements provided by the modifications will build upon these reference temperatures. It is important to note that since start-up curves are being used as the reference parameter for start-up time reduction that not all temperature increases of the final state of the turbine necessarily lead to a faster start-up. The reason is that the temperature levels for start-up time reduction are not distributed equally between the types of curves, this meaning that for certain start-up curve improvements the required temperature increase is larger than for others. The parasitic consumption of the heat blankets modification was also integrated to the latter simulations.

Fig. 6(left) shows the total annual reductions of turbine start up times as a function of the implemented enhancements. Likewise Fig. 6(right) reflects the corresponding improvements in annual electricity production within the same range. In both figures the threshold for improving the start-up times and annual improvements beyond warm starts can be observed at the 10%, 20% and 30% levels of start-up time reduction This threshold is related to the temperature levels between the start-up curves for warm and hot start respectively.

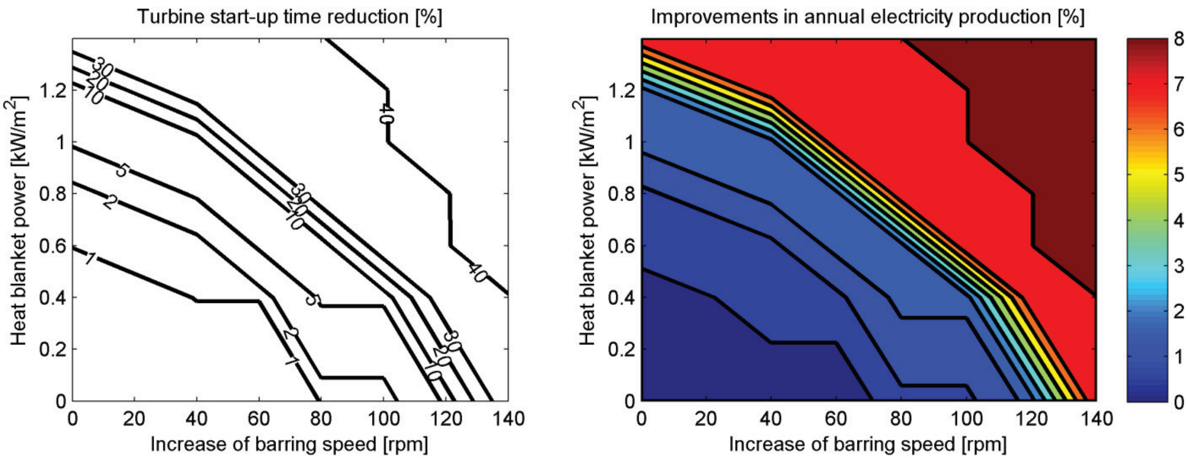

Fig. 6 Percentage of turbine start-up time reductions (left) and improvements in annual electricity production (right) as a function of the implemented turbine temperature maintaining modifications.

In addition to positively affecting the annual power output of the power plant, the temperature maintaining modifications also have a beneficial impact on the lifetime of the turbine component and therefore on its related maintenance costs. This is reflected in Fig. 7(right) with the percentage of improvement of the fraction of EOHs to EOH. EOHs are a measure of accounting for turbine start-ups within the normal operating hours of the component and its lifetime consumption through operation. The improvements on EOHs are directly coupled with the increased number of hot starts, Fig. 7(left), given than these are imply a shorter time of transient thermal stress to the turbine. The EOH however also depend on the NOH of the plant, which are increasing directly with the enhancements given that the power plant is available during longer periods due to faster turbine start-ups. The fraction of EOHs to EOH therefore reflects the corresponding improvements for each case.

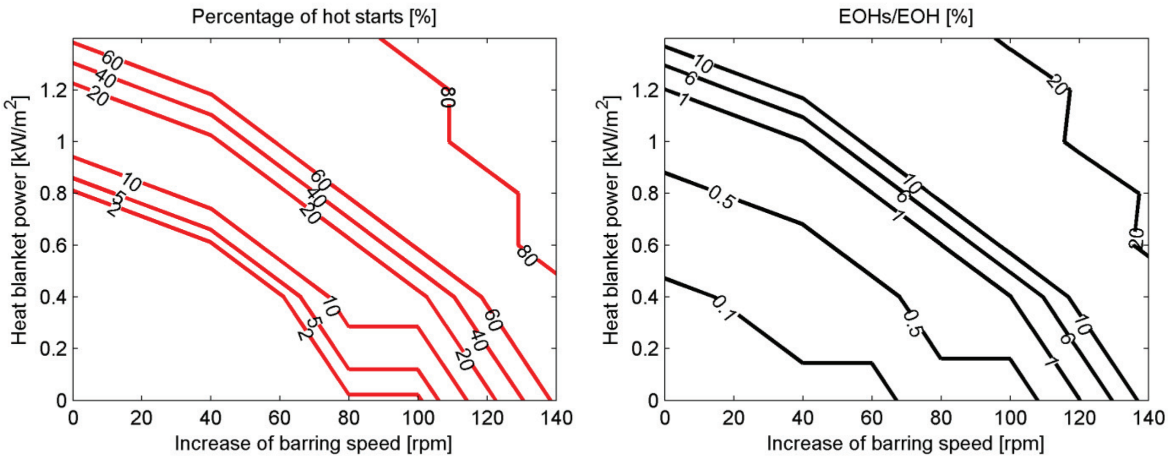

Fig. 7 Percentage of turbine hot starts (left) and improvements in the fraction of equivalent operating hours due to start with the equivalent operating hours of the plant of the plant (right) as a function of the implemented turbine temperature maintaining modifications.

5. Conclusions

In days with intermittent direct irradiation, DSG-STPP can undergo multiple start-ups during a 24h period. This raises the interest of achieving faster plant start-ups in order to harness the solar energy as soon as it becomes available. The startup speed of the power plant is limited by that of the steam turbine component. Therefore, on this paper the impact of two turbine temperature-maintaining operational modifications was evaluated in the dynamic simulation of a DSG-STPP model in order to observe the performance improvements on the power plant due to faster starts. A parametric study was then carried out in order to calculate the impact the combined modifications on the annual electric output of the plant and on the lifetime consumption of the turbine. The studies were carried out considering a whole year of power plant operation. It was seen that the implementation of the turbine flexibility enhancements had a positive effect on the performance of the plant.

In general, maintaining the temperature of the steam turbines during offline periods would seem to be a viable possibility for DSG-STPP operation. Especially for those configurations which do not comprise thermal energy storage. The modifications studied in this paper show great potential for achieving better power plant performance through faster turbine start-ups leading up to 8% increase of annual electricity production.

It should be noted that the results obtained in this paper are not strongly coupled with the transient temperature states of the turbine, but instead it uses typical start-up curves provided by a turbine manufacturer. For future work, the strong coupling between the dynamic power plant model, the turbine thermal model and turbine start-up curves will be considered for the performance analysis of concentrating solar power systems. In addition, future work will also comprise more detailed analysis into the potential improvement of the power plant in terms of revenues and maintenance costs as well as an overall quantification of the electricity consumption of the implemented measures.

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